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by

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Abstract

The high-frequency cutoff of synchrotron radiation resulting from electrons with an anisotropic pitch-angle distribution is investigated. It is shown that this effect could be responsible for the high-frequency cutoffs of Type IV bursts at decimeter, meter and decameter wavelengths.

The radio spectrum of Type IV solar bursts at meter and decimeter wavelengths is in general characterized by narrow-band emission with at least one maximum and by quite sharp low and high-frequency cutoffs (Takakura, 1963). It was first suggested by Ramaty and Lingenfelter (1967) that the steep spectrum at low frequencies below the maximum is the result of the Razin effect, i.e., the suppression of synchrotron emission owing to the influence of the ambient coronal plasma.

In the framework of ordinary synchrotron theory, the steep spectrum above the maximum, which on occasions may vary as rapidly as ν^{-4}, could in principle be produced by a correspondingly steep electron spectrum, or by an electron distribution with a high-energy cutoff. Direct measurements of relativistic solar electrons near the earth (Cline and McDonald, 1968; Simnett, private communication), however, indicate that the spectrum of these particles, up to an energy of at least 6 Mev, is in general of the form $E^{-\Gamma}$, where $\Gamma \approx 3$, while for typical coronal magnetic fields, the radio observations require values of Γ as high as 9. This discrepancy may indicate that the electrons that were observed near the earth and those responsible for the Type IV emission at the sun are of different origins, and may have, therefore, different energy spectra; or that the electrons which produce the radiation remained trapped in relatively strong magnetic fields which produced the high-energy cutoff by synchrotron losses. Both possibilities, however, seem to be contradicted by a recent observation of Simnett et al. (1969), who

showed that relativistic electrons, which must have been produced by an explosive event in the chromosphere, remained trapped in the corona without significant change in their spectral distribution for periods as long as a few days.

As an alternative explanation we wish to suggest that the high-frequency cutoffs of Type IV solar bursts may be caused by electrons having an anisotropic pitch-angle distribution. Since the radiation pattern of synchrotron emission becomes narrower as the energy of the particles is increased, the radiation of the high-energy electrons in an anisotropic distribution is strongly suppressed if the electrons are viewed from a direction other than that of maximum anisotropy. This results in an effective high-frequency cutoff, which when coupled with the Razin effect at low frequencies produces narrow-band synchrotron spectra much like those observed for Type IV metric and decimetric emission.

In order to illustrate this effect, we use the general theory of gyro-synchrotron emission and absorption in a magneto-active plasma which was treated in detail in a previous paper (Ramaty, 1969). We consider an ensemble of electrons with energy spectrum $u\ (\gamma) \sim (\gamma-1)^{-3}$ and pitch-angle distribution $g(\varphi) \sim \sin^m \varphi$, moving in a static, homogeneous and uniform magnetic field immersed in a homogeneous, cold electron plasma. The radiation intensities from an optically thin source are shown in Figure 1. We have considered various values of the observation angle θ (with respect to the static field) for the limiting case of maximum anisotropy corresponding to all electrons in circular orbits,

as well as various anisotropies for a fixed value of θ.

The steep spectra at low frequencies are caused by the Razin effect, which may be characterized by a parameter $\alpha = 1.5\ \nu_B/\nu_p$, where ν_B and ν_p are the ambient gyro and plasma-frequencies respectively. For a single electron of Lorentz factor γ, there is no significant low-frequency suppression if $\alpha\ \gamma \gtrsim 1$, whereas if $\alpha\ \gamma << 1$, the entire emission spectrum is strongly suppressed. The high-frequency cutoffs result from the anisotropy, and, as can be seen, they become steeper as either or both the anisotropy and $(\pi/2 - \theta)$ are increased.

For a detailed comparison of the calculated and observed Type IV emissions, it is necessary to make assumptions about the magnetic field, the ambient density and the electron distribution in the emitting region. Several authors (Boischot and Daigne, 1968; Ramaty and Lingenfelter, 1968; Simon, 1969; Bohlin and Simon, 1969) have considered the 1100 UT, 14 September, 1966 Type IV event. This burst, which was first observed on the west limb of the sun at an altitude of about $1R_\odot$, had a narrow-band spectrum which peaked at $\sim$ 200 MHz with sharp low and high-frequency cutoffs (Boischot and Clavelier, 1967, 1968). Using typical streamer densities at an altitude of $1R_\odot$, it was shown that for a magnetic field of $\sim$ 1 gauss the low frequency cutoff could indeed be caused by the Razin effect. Since all the treatments mentioned above were based on the assumption that the radiating electrons were isotropic, the high-frequency cutoff had to be attributed to a high-energy cutoff, even though

direct electron measurements at the earth on September 14, 1966 (Cline and McDonald, 1968) did not reveal any break in the spectrum at the energies of interest.

For a detailed numerical calculation appropriate for an anisotropic distribution it is necessary to assume a pitch-angle distribution for the radiating electrons and the angle of observation with respect to the ambient magnetic field. These quantities, however, depend in a complicated way on the acceleration, propagation and storage of the electrons and on the magnetic configuration of the trapping region. We defer this for future investigation. We should point out, however, that anisotropic distributions peaked toward large pitch-angles would arise from both a Fermi and a betatron acceleration mechanism. Furthermore, if a given electron distribution is trapped on a magnetic loop in the corona, particles with small pitch-angles would be removed from the trapping region by collisions with the ambient medium, since their trajectories would mirror in denser chromospheric regions. On the other hand, synchrotron losses which could remove particles with large pitch-angles are negligible for typical coronal fields and time scales up to at least several days. There seems to be, therefore, a real possibility of maintaining in the corona a highly anisotropic distribution of the kind required to account for the high-frequency cutoffs of Type IV bursts.

We wish to comment on the polarization of the radiation and on the role of reabsorption by the radiating electrons

themselves. It was shown by Holt and Ramaty (1969) that for impulsive microwave bursts, reabsorption must be taken into account, and that the transition from the optically thick to the optically thin regime may lead to the reversal of the sense of circular polarization. The simultaneous effects of the Razin suppression and reabsorption were treated by Ramaty (1969). In this paper, a graph was given for the transitional values of the quantity N/BA as a function of the parameter α, mentioned above, where N is the total number of electrons above 100 kev for $\Gamma=-3$, B is the magnetic field and A is the radiating area, both in cgs units. For example, for $\alpha = 0.25$ and $\alpha = 0.1$, these are $\sim 5\text{x}10^{15}$ and $5\text{x}10^{19}$ respectively. For larger values of N/BA, the source is optically thick at low-frequencies, whereas for smaller values of N/BA, at low-frequencies the Razin effect dominates, and the source is optically thin at all frequencies. For an optically thin source the radiation is predominantly in the extraordinary mode, whereas if the source is optically thick, the ordinary mode radiation will be larger than that in the extraordinary mode. This is a special result for non-thermal sources, since in an optically thick thermal source, because of Kirchoff's law, the radiation intensity will be the same for both modes. These results are qualitatively the same for both isotropic and anisotropic electron distributions. However, since the dominance of the ordinary mode in an optically thick source is caused by the greater relative contribution of the higher energy electrons to

this mode of wave propagation, the anisotropy will have the net effect of lowering the transition frequency from the optically thick to the optically thin regimes. Furthermore, for a given α, the transitional value of N/BA will be larger for the anisotropic distribution than for the isotropic one.

Using the calculations of Ramaty and Lingenfelter (1968) (appropriate for an isotropic distribution with a high-energy cutoff) and assuming that the radiating electrons at the sun have a power law spectrum $\sim(\gamma-1)^{-3}$, we find that for $\alpha = 0.25$ and $\alpha = 0.1$, the total number of electrons greater than 100 kev required to account for the 1100 UT, 14 September, 1966 burst must have been 4×10^{34} and 4×10^{36}, respectively. The magnetic field values appropriate for these choices of α are 4.1 and 0.86 gauss, so that the values of N/BA become 1.5×10^{14} and 7.3×10^{16}, respectively. By comparing these with the transitional values of N/BA, mentioned above, we see that the 14 September 1966 Type IV burst must have been optically thin and polarized according to the extraordinary mode. Since Faraday rotation in the source may have been large, the polarization is circular and the actual sense of rotation depends on the direction of the field in the radiating region.

Recent observations of solar radio bursts at decimeter (Michael et al, 1968; Castelli, private communication) and decameter (Warwick, 1968 and private communication) wavelengths have revealed emissions with extremely narrow-band frequency spectra. If characterized by a power law, the spectrum of these events, below and above the maximum would be of the form $\nu^{\pm x}$, respectively, where $x \sim 10$. Both Michael et al. (1968) and

Warwick (1968) have attributed the low-frequency cutoff to the Razin effect. In view of the results of the present letter, we wish to suggest that the high-frequency cutoffs are caused by an anisotropic electron distribution.

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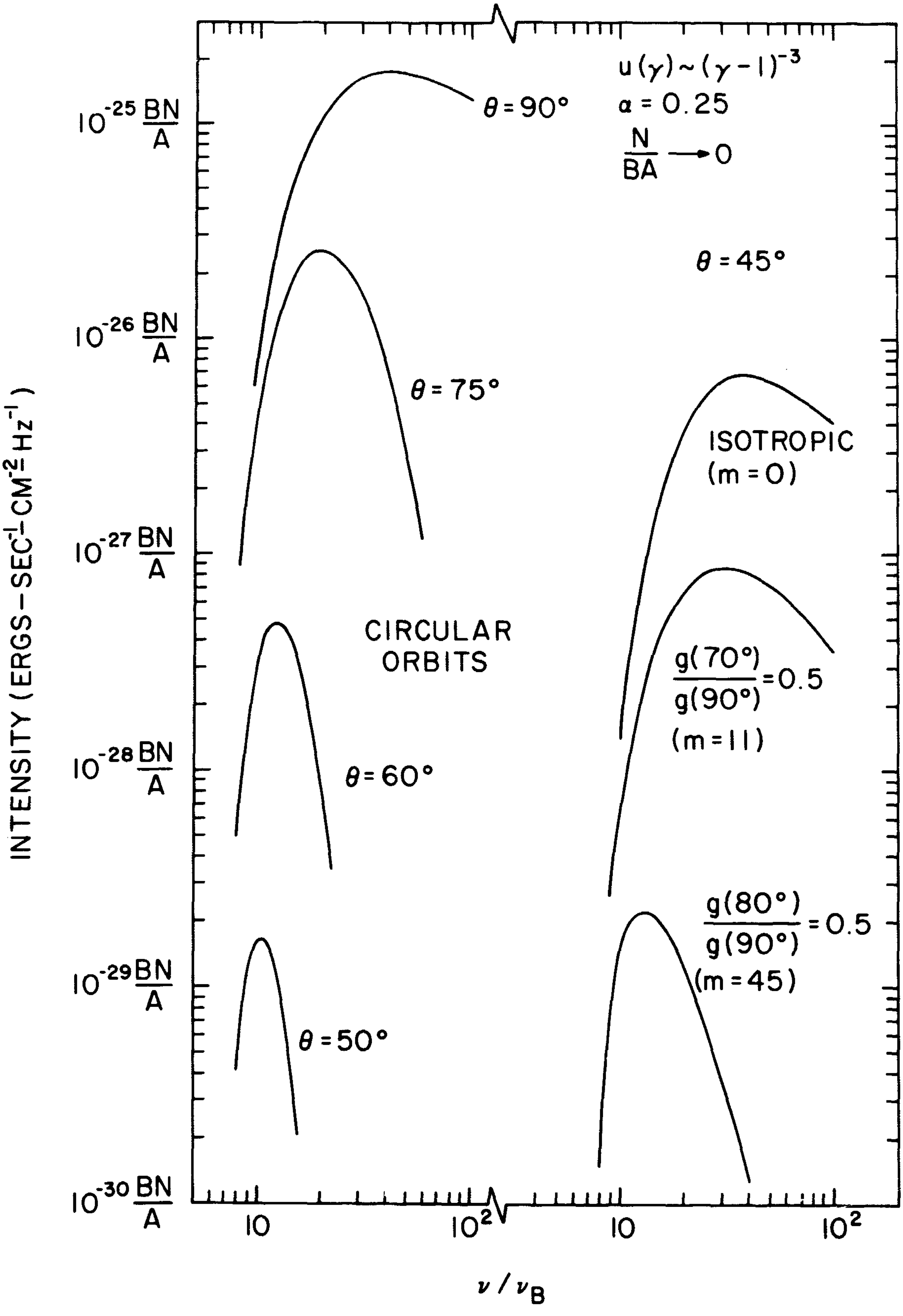
FIGURE CAPTION

Figure 1: Radiation intensity from an anisotropic optically thin gyro-synchrotron source for a Razin parameter $\alpha = 0.25$.



$u(\gamma) \sim (\gamma - 1)^{-3}$
$\alpha = 0.25$
$\frac{N}{BA} \rightarrow 0$
$\theta = 90°$
$\theta = 75°$
$\theta = 60°$
$\theta = 50°$
CIRCULAR ORBITS
$\theta = 45°$
ISOTROPIC (m = 0)
$\frac{g(70°)}{g(90°)} = 0.5$ (m = 11)
$\frac{g(80°)}{g(90°)} = 0.5$ (m = 45)
INTENSITY (ERGS-SEC^{-1}-CM^{-2}-Hz^{-1})
$10^{-25}\frac{BN}{A}$
$10^{-26}\frac{BN}{A}$
$10^{-27}\frac{BN}{A}$
$10^{-28}\frac{BN}{A}$
$10^{-29}\frac{BN}{A}$
$10^{-30}\frac{BN}{A}$
10
10^2
10
10^2
ν / ν_B

END

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